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Aspect influences on soil water retention and storage

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Abstract:

Many catchment hydrologic and ecologic processes are impacted by the storage capacity of soil water, which is dictated by the profile thickness and water retention properties of soil. Soil water retention properties are primarily controlled by soil texture, which in turn varies spatially in response to microclimate-induced differences in insolation, wetness and temperature. All of these variables can be strongly differentiated by slope aspect. In this study, we compare quantitative measures of soil water retention capacity for two opposing slopes in a semi-arid catchment in southwest Idaho, USA. Undisturbed soil cores from north and south aspects were subjected to a progressive drainage experiment to estimate the soil water retention curve for each sample location. The relatively large sample size (35) supported statistical analysis of slope scale differences in soil water retention between opposing aspects. Soils on the north aspect retain as much as 25% more water at any given soil water pressure than samples from the south aspect slope. Soil porosity, soil organic matter and silt content were all greater on the north aspect, and each contributed to greater soil water retention. These results, along with the observation that soils on north aspect slopes tend to be deeper, indicate that north aspect slopes can store more water from the wet winter months into the dry summer in this region, an observation with potential implications on ecological function and landscape evolution. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS storage; soil moisture; aspect; watershed; semi-arid; water retention

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INTRODUCTION

Arid and semi-arid ecosystems are defined primarily by water limitation; the growing season is often dictated by the duration of water availability. In upland arid and semi-arid ecosystems, where precipitation is limited for extended periods and depth to groundwater typically limits availability to plants, water stored in the soil profile can be the primary bio-available reservoir. Topographic indexing methods are commonly used to describe the distribution of soil moisture (Famiglietti *et al.*, 1998; Grayson *et al.*, 1997; Western *et al.*, 1999). In semi-arid environments, however, seasonally dry conditions occur during which topography has little influence on moisture redistribution (Grant *et al.*, 2004, McNamara *et al.*, 2005, Williams *et al.*, 2009). The initial variability of rainfall or snowmelt coupled with complex redistribution of water in the snowpack and soil by heterogeneous drainage and evapotranspiration can result in complex spatial patterns in soil moisture (Famiglietti *et al.*, 2008). In these environments, soil water retention will determine how much water is discharged to the adjacent streams and underlying groundwater and determine soil water availability during the growing season. Accordingly, it is essential to understand how water inputs are retained in catchments, in addition to the more commonly studied water release mechanisms.

The storage capacity of a soil profile depends on soil depth and the capacity of the soil to retain water under stresses imposed by gravitational drainage and evapotranspiration. The relationship between soil water pressure (pressure head) and volumetric moisture content is represented by the soil water retention curve (SWRC). The SWRC, coupled with a similar relationship between hydraulic conductivity and moisture content or pressure head, describe the soil hydraulic properties. Both curves are needed to solve the Richards equation governing the temporal variability of soil moisture content during infiltration and gravitational redistribution. Considering flow in the vertical direction, the Richards equation can be expressed as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right]$$

where θ is the volumetric moisture content (L^3/L^3), K is hydraulic conductivity (L/T), h is pressure head (L) (which can be negative in the vadose zone), t is time (T) and z is distance in the vertical direction, positive upwards (L). The shape of the SWRC, or the $\theta(h)$ function is a fundamental characteristic of the soil (Childs, 1940). Soil properties are typically expressed in terms of soil texture, but other properties such as structure, organic carbon content and bulk density exert a primary control on the SWRC and are

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14. ABSTRACT **Many catchment hydrologic and ecologic processes are impacted by the storage capacity of soil water, which is dictated by the profile thickness and water retention properties of soil. Soil water retention properties are primarily controlled by soil texture which in turn varies spatially in response to microclimate-induced differences in insolation, wetness and temperature. All of these variables can be strongly differentiated by slope aspect. In this study, we compare quantitative measures of soil water retention capacity for two opposing slopes in a semi-arid catchment in southwest Idaho, USA. Undisturbed soil cores from north and south aspects were subjected to a progressive drainage experiment to estimate the soil water retention curve for each sample location. The relatively large sample size (35) supported statistical analysis of slope scale differences in soil water retention between opposing aspects. Soils on the north aspect retain as much as 25% more water at any given soil water pressure than samples from the south aspect slope. Soil porosity, soil organic matter and silt content were all greater on the north aspect, and each contributed to greater soil water retention. These results, along with the observation that soils on north aspect slopes tend to be deeper indicate that north aspect slopes can store more water from the wet winter months into the dry summer in this region, an observation with potential implications on ecological function and landscape evolution.**					
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therefore dominant factors influencing catchment water retention as a whole.

The spatial distribution of soil water retention relies on the distributions of soil properties, which are commonly understood to depend on Jenny's (1941) five soil forming factors: regional climate, potential biota, topography, parent material and time. In arid and semi-arid environments, differences in soil development within a common lithology are readily observed among different microclimates. At the local scale, soil moisture can be strongly controlled by vegetation patterns (Madsen *et al*., 2008). In complex terrain, landscape scale patterns of moisture and vegetation coincide primarily with aspect, which influences the distribution of incoming solar energy at the land surface.

While the instantaneous impacts of aspect on snowmelt, evapotranspiration, and other local energy balance problems are well studied, the longer timescale influences on landscape properties and the feedbacks with hydrological processes are less understood (Broxton *et al*., 2009). Given that aspect influences the surface energy balance, it is reasonable to expect that soils and associated ecosystems will develop differently; a trend often noted in the soil literature (Losche, 1970). Indeed, such aspect differences have been documented for hydraulic conductivity (e.g. Casanova *et al*., 2000) and soil depth (e.g. Khumalo, *et al*., 2008; Smith, 2010; Tesfa *et al*., 2009). Despite its potentially profound ecological importance, there are limited data explicitly documenting differences in soil water retention with aspect (e.g. Leij *et al*., 2004; Herbst *et al*., 2006), likely due in part to the difficulty in making such measurements.

In this study, we have experimentally quantified aspect differences in soil water retention capacity in a semi-arid catchment in southwest Idaho, USA. Using a North-South oriented transect, we compare SWRCs and soil physical properties, evaluate the relationships between soil physical properties and water retention and discuss how these results affect soil water storage and the co-evolution of geomorphic, hydrologic and biologic systems.

SITE DESCRIPTION

This study was conducted in the 27 km^2 Dry Creek Experimental Watershed, located north of Boise Idaho, USA. The upper elevations are classified using the Köppen system, as moist continental climate and dry summers (Dsa), while the lower elevations are classified as steppe summer dry climate (BSa) (Henderson-Sellers and Robinson, 2001). The 650-m study transect spans a canyon; one slope is mostly north aspect (~365 m), while the other is mostly south aspect (~285 m). The average slope angles on the south and north aspects are 25 degrees and 32 degrees, respectively.

Soils in the study area are derived from Idaho Batholith parent material, a granitic intrusion that is 80 million years old. Soils fall into three classifications in the USDA SSURGO 2.0 database (Soil Survey Staff, 2009). The soils along the south aspect part of the transect (sites 1–15) are classified as mesic Ultic Haploxerolls with Pachic and Lithic modifiers. Soils along the lower elevation part of the north aspect (sites 17–31) are classified as frigid Ultic Haploxerolls, while the upper elevation sites (sites 32–25) are classified as mesic Ultic Haploxerolls with Entic and Lithic modifiers. In all cases, the vegetation on the south aspect part of the transect consists primarily of low sagebrush (*Artemisia arbuscula*), big sagebrush (*Artemisia tridentata)* and assorted forbs and grasses. Vegetation along the north aspect portion of the transect is dominated by fir species (*Pseudotsuga spp.)* with an understory of shrubs.

METHODS

Thirty-five sampling sites were located at approximately 20 m intervals (Figure 1). Sampling locations along the south aspect slope were centered on an aspect of 155 degrees ranging between 142 degrees and 169 degrees, while those along the north aspect slope were centered on an aspect of 313 degrees ranging between 268 degrees and 006 degrees. The south aspect slope ranges in elevation from 1361 to 1490 m above mean sea level (msl), and the north aspect slope ranges in elevation from 1361 to 1579 m above msl.

Soil water retention measurement

Undisturbed soil cores with a nominal diameter and height of 5.4 cm and 3.0 cm, respectively, were removed at each sampling location using a hand-operated soil core extractor and subjected to a progressive drainage experiment using an automated multistep outflow apparatus described by Figueras and Gribb (2009). Cumulative outflow data and steady state soil moisture as a function of pressure head data (i.e. $\theta(h)$) obtained from the experiments were used as inputs for HYDRUS 1D (Simunek *et al*., 2005) to estimate the SWRCs for each sampling location.

Soil cores were wetted with a solution of de-aired water, 0.30 g/L Thymol, and 0.27 g/L $CaCl_2$ to prevent bacterial growth and clay dispersion (Klute and Dirksen, 1986) prior to testing. One-bar ceramic disks (part number 1400B01M1-3, Soil Moisture Equipment Corporation, Santa Barbara CA) were used in the Tempe cells. Samples were allowed to imbibe water for at least 24 h prior to testing. Applied pressure steps of approximately 20, 40, 60, 100, 200, 400 and 600 cm were used, and each pressure step was maintained for approximately 24 h. After outflow ceased at the greatest applied pressure step, the soil core was removed, weighed, dried for 24 h at 105 °C, and weighed again to determine the volumetric moisture content at the final pressure step. Outflow volumes from the soil sample were then used to calculate θ at each previously applied pressure step. The tests did not have uniform pressure steps; therefore, the soil moisture *versus* pressure head data were used to estimate the van Genuchten (1980) soil hydraulic parameters, which were used to estimate soil moisture values at specific pressure heads for comparing moisture retention behavior between the two slopes.

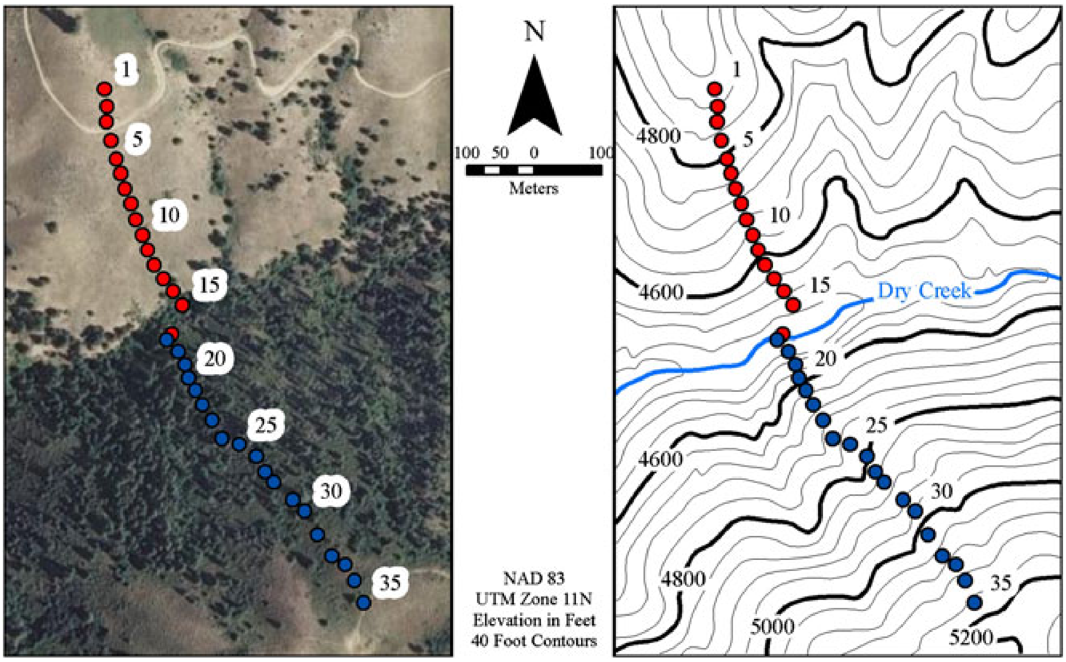

Figure 1. Study site in the Dry Creek Experimental Watershed. Red dots show south-facing sampling locations; blue dots are on the north-facing slope. Contours are in meters

Soil physical properties

After multistep outflow testing, the soil cores were dried and subjected to mechanical sieving and laser diffraction (Malvern Mastersizer 2000, Malvern Instruments Ltd., Malvern, Worcestershire, UK) to determine the soil textural class fractions by weight according to the USDA method, which employs the following size standards: gravel > 2 mm, 2 mm < sand < 0.05 mm, 0.05 mm < silt < 0.002 mm, and clay < 0.002 mm (Soil Survey Staff, 1999). The organic carbon content (by weight basis) of a soil sample from each sampling location was determined using a Flash EA 1112 Elemental Analyzer (Thermo Fisher Scientific Inc., Waltham MA). Samples were extracted from 10 cm below ground surface using a manual coring device, placed in plastic bags and frozen to prevent degradation prior to analysis.

Data analysis

We used box plots and the two-sample Kolmogorov–Smirnov (KS) test (e.g. Massey, 1951), a non-parametric comparison of the empirical cumulative distribution functions of two populations, to evaluate differences between soil physical and hydraulic properties from 16 sampling locations on the south aspect part of the transect (SA) and those for the 19 sampling locations along the north aspect part of the transect (NA). Whereas other researchers have used correlation analysis to explore relationships between topographic variables and soil properties (e.g. Leij *et al.*, 2004), the clustered nature of our sample locations around generally north facing and generally south facing aspects precluded use of correlation analysis in this study.

In situ soil moisture measurement

In situ measurement of the volumetric soil moisture content at each sampling location was performed using a Campbell Scientific (Logan, UT) CR23X datalogger, TDR100 waveform generator, and a CS605 probe assembly. The CS605 probe was shortened from 30 cm to 15 cm according to Campbell Scientific Application Note 2S-H. The CR23X was programmed using LoggerNet version 3.4.1. Each manually initiated sampling event resulted in four TDR waveforms being transmitted to the CS605 probe. The apparent dielectric conductivity (Ka) that was recorded by the CR23X represented the average Ka of the four waveforms. A site-specific calibration equation was developed with soil collected from a mid-elevation, south aspect location, which had a grain size distribution representative of the average of all sample locations. A fourth order polynomial provided the best fit of the data. On each sampling date, four individual measurements were made within a 1 m^2 area at each sampling location.

RESULTS

Soil properties and aspect

Slope average physical properties of soils differ significantly by aspect ($\alpha = 0.05$) as shown by the boxplots in Figure 2, and the results of two-sample KS tests (Table I). The NA soil samples are generally finer grained with somewhat less sand, more silt and more clay than SA soils (Table I), and greater saturated moisture content values, θ_s. The slope average differences in organic carbon (1.39% for SA, 2.75% for NA) and bulk density (1.57 g/cm^3 for SA, 1.37 g/cm^3 for NA) (or porosity (0.41 for SA, 0.50 for NA)), and θ_s (0.41 for SA, 0.50 for NA) are notable. Since these properties are strongly covariate, differences in these properties between the two aspects were consistently significant. These strong divisions in soil properties by aspect were not observed by Leij *et al.* (2004); however,

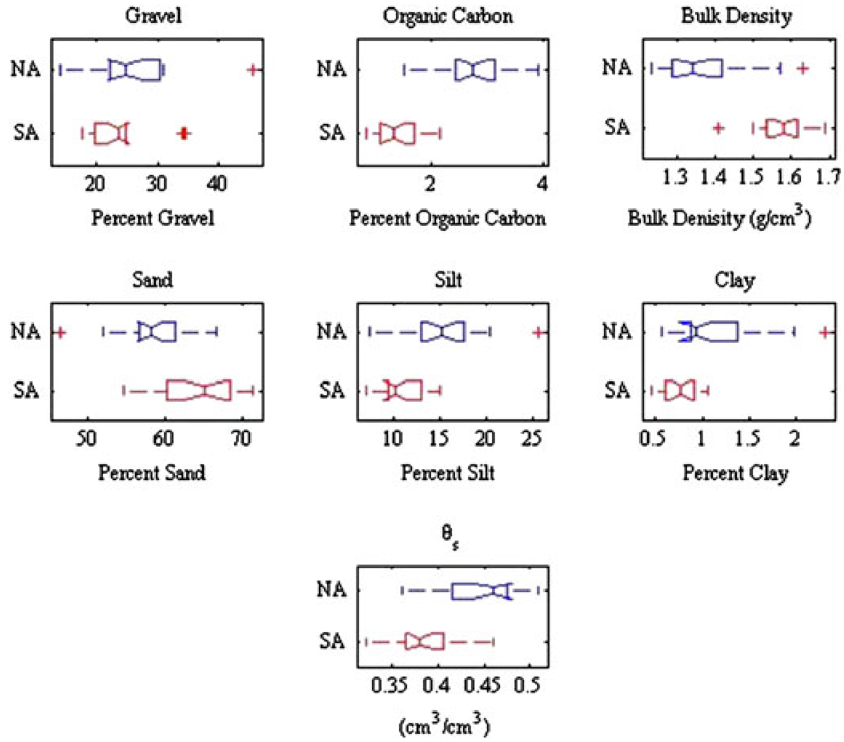

Figure 2. Boxplots of the north and south aspect values for the following soil physical attributes: gravel, bulk density, sand, silt, clay, organic carbon and θ_s

Famiglietti *et al*. (1998) found strong positive correlations between aspect and clay content, and strong negative correlations between aspect and porosity. The increase in θ_s is consistent with the results of Leij *et al*. (2004) and Herbst *et al*. (2006), as both studies showed that θ_s values increase as aspect becomes more northerly. The value of θ_s is important to the alteration of soil water retention over the soil water potential domain, as shown by SWRC curves (Figure 3a).

Whereas the van Genuchten parameters estimated by inverse analysis do not show significant differences between the south and north aspect slopes (results not shown), the SWRCs do, with the north aspect soils retaining more water by volume of soil (in general), across a range of pressure heads (Figure 3a). The absence of strong differences in the inversely estimated van Genuchten parameters may be due to the difficulty in achieving unique parameter estimates by this approach (Eching and Hopmans 1993). To overcome this limitation, the estimated parameters were used to calculate $\theta(h)$ from $h = 0$ to $h = -1000$ cm, and the NA and SA groups were then compared using boxplots (Figure 3c) and KS tests (Table I). At all pressure heads, the differences in moisture contents between the NA and SA groupings were significant at the 95% confidence level. Note that when the SWRC curves are plotted in terms of effective saturation, $\theta(h)/(\theta_s - \theta_r)$, (e.g. Gribb *et al*., 2009), the NA and SA curves no longer separate into two distinct groups (Figure 3b). Boxplots of the effective saturation show that the populations of soil moisture at different pressure heads are no longer significantly different when curves are normalized in this way (Figure 3d).

Soil moisture and aspect

Soil moisture was measured on 27 days for the south aspect slope, and 25 days for the north aspect slope during the spring and summer of 2009 (Figure 4). Mean soil moistures for north and south aspects behave similarly, increasing similarly to precipitation inputs (Figure 4, right axis), and tend to dry together. However, the north aspect has consistently greater mean soil moisture. This trend persists well past the initial post snowmelt drydown in the spring, indicating that the later input of snowmelt on north aspect slopes is not likely responsible for the observed differences in soil moisture between the north and south aspects. When the soil moisture on the two aspects are compared using a two-sample KS test (for the 25 days on which both aspects were sampled), the differences between the aspects are significant at the 95% confidence level. The slope-average soil moisture conditions are consistent with greater water retention on north aspect slopes, which is consistent with observed differences in SWRCs. While it is clear that soil hydraulic properties contribute to this trend, the relative importance of their role with respect to other driving factors including solar radiation, air temperature and redistribution is unknown.

DISCUSSION

Greater silt fraction of the soil particle size distribution (Table I) is inferred to be the dominant control on increased soil water retention on north aspect slopes, especially in the 'dry end' of the SWRC. Differences in organic carbon, and consequently bulk density and porosity, account for

Table I. Soil properties of sampling locations and results of KS test results for these properties (Y = significant difference between populations of values on north- and south-facing slopes, N = no significant difference)

Site #	Gravel %	Sand %	Silt %	Clay %	Organic Carbon %	Bulk Density (g/cm^3)	Porosity (-)	θ_s (-)
Sampling locations								
South-facing slope (SA)								
1	24.9	61.2	13.1	0.78	1.92	1.56	0.41	0.41
2	23.2	61.4	14.3	1.06	1.27	1.62	0.39	0.36
3	24.8	59.2	15.0	1.0	1.85	1.41	0.47	0.44
4	18.2	66.7	14.1	0.95	0.89	1.55	0.42	0.4
5	21.3	64.7	13.1	0.88	0.96	1.61	0.39	0.38
6	34.5	54.9	9.9	0.73	1.52	1.54	0.42	0.39
7	34.4	54.7	10.1	0.77	1.34	1.58	0.4	0.36
8	19.8	66.9	12.3	0.98	1.34	1.64	0.38	0.37
9	34.0	58.5	7.0	0.45	1.13	1.69	0.36	0.35
10	17.9	70.4	10.9	0.76	0.81	1.6	0.4	0.38
11	19.4	70.7	9.4	0.54	1.03	1.5	0.44	0.43
12	20.4	68.6	10.3	0.67	1.26	1.53	0.42	0.39
13	24.0	65.0	10.3	0.67	2.14	1,50	0.43	0.46
14	19.9	71.2	8.4	0.53	1.23	1.58	0.4	0.32
15	24.8	65.0	9.5	0.77	1.96	1.59	0.4	0.37
16	24.1	68.0	7.5	0.53	1.55	1.62	0.39	0.38
North-facing slope (NA)								
17	24.8	57.5	16.8	0.89	3.69	1.33	0.50	0.47
18	14.2	66.6	17.9	1.37	2.76	1.26	0.53	0.51
19	25.9	57.9	15.2	0.94	2.18	1.28	0.52	0.42
20	30.7	56.5	12.0	0.88	2.25	1.40	0.47	0.46
21	23.6	61.0	14.4	1.03	3.17	1.23	0.54	0.51
22	24.5	61.4	13.2	0.86	2.50	1.35	0.49	0.47
23	29.0	60.2	10.2	0.64	3.14	1.28	0.52	0.47
24	30.8	57.2	11.1	0.92	1.49	1.57	0.41	0.36
25	18.5	59.0	20.4	1.99	1.88	1.43	0.46	0.41
26	17.0	55.0	25.7	2.32	2.77	1.29	0.51	0.49
27	30.8	51.9	15.9	1.36	2.41	1.43	0.46	0.41
28	23.3	56.5	18.6	1.59	2.63	1.37	0.48	0.46
29	25.3	58.1	15.7	0.87	2.84	-	-	-
30	31.0	54.2	13.9	0.88	3.72	1.29	0.51	0.48
31	26.2	59.2	13.8	0.83	3.12	-	-	-
32	22.1	61.6	15.3	0.93	3.92	-	-	-
33	23.0	63.2	12.9	0.97	2.74	1.40	0.47	0.43
34	45.5	46.5	7.40	0.57	2.54	1.63	0.39	0.36
35	16.6	63.2	18.7	1.53	2.45	1.33	0.50	0.44
SA average	24.1	64.19	10.95	0.75	1.39	1.57	0.41	0.39
NA average	25.4	58.2	15.2	1.1	2.7	1.4	0.50	0.45
Overall Ave	24.8	61.0	13.3	1.0	2.1	1.4	0.45	0.42
KS Test	N	Y	Y	Y	Y	Y	Y	Y

differences at or near saturation. These documented aspect differences in soil properties indicate that north aspect slopes have the capacity to store considerably more water. For example, a general approximation of field capacity is the moisture content that remains in the soil at $h = -340$ cm (Dingman, 2002). This pressure head corresponds to volumetric soil moisture contents of approximately 0.16 and 0.21 on south aspect and north aspect slopes, respectively (Figure 3a). In other words, soils on north aspect slopes have approximately 25% greater water retention capacity. For a soil depth of 1 m, that retention difference translates into 5 cm of water, or approximately 10% of the annual precipitation at the site. This aspect difference in water retention is further accentuated by deeper soils on north aspect slopes (Smith, 2010; Tesfa *et al.*, 2009). When these differences are coupled with reduced solar insolation on north aspect slopes, elevated moisture contents are sustained (Figure 4).

The aspect differences in soil properties are likely not due to a singular cause, but arise from complex interactions between microclimate, vegetation, lithology, material source (e.g. *in situ* weathering or loess deposition), and erosion. South aspect soils receive considerably more insolation than the north aspect soils, while both aspects share nearly all other physical variables that dictate soil development including parent material, precipitation, elevation, slope position. Differences in insolation have also, apparently, distinguished the two hillsides with respect to vegetation density, soil carbon content and soil depth, all greater on the north aspect slope (Smith, 2010). The north

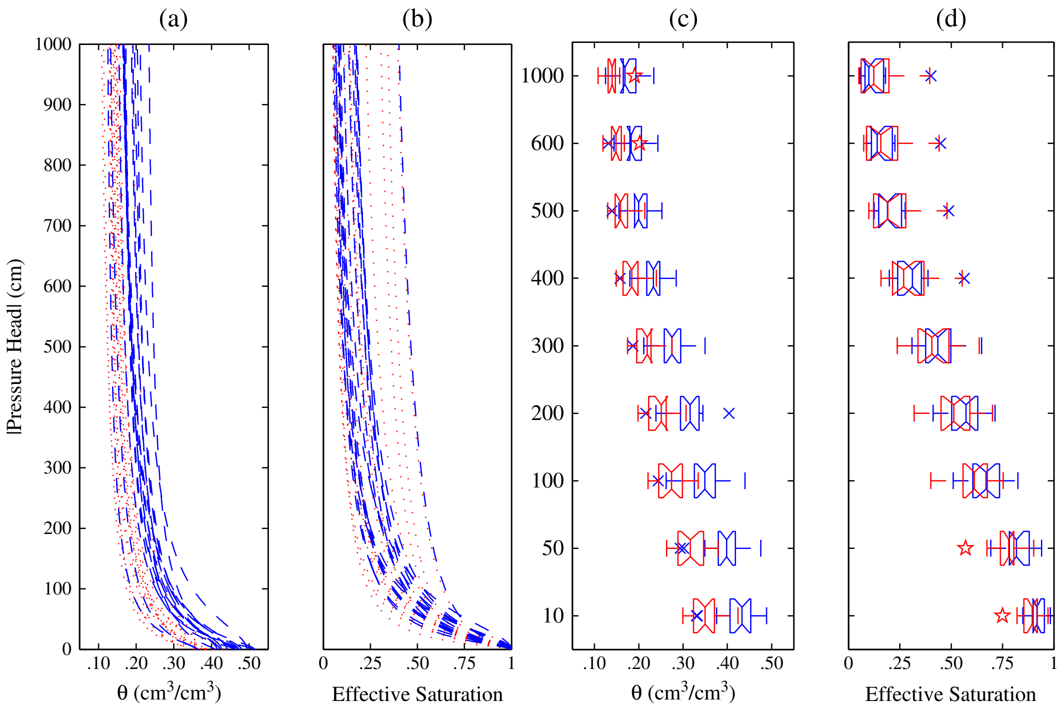

Figure 3. (a) The SWRCs of the sample locations, with the north aspect soils (blue) tending to retain more water at a given pressure head than those of the south aspect (red). (b)When the effective saturation curves are plotted, the NA and SA groupings become more intermixed. (c) Boxplots comparing the north and south aspect soils show significant differences across a large range of pressure heads. (d) Boxplots of the effective saturation curves show that scaling eliminates the difference in soil water retention between the two slopes

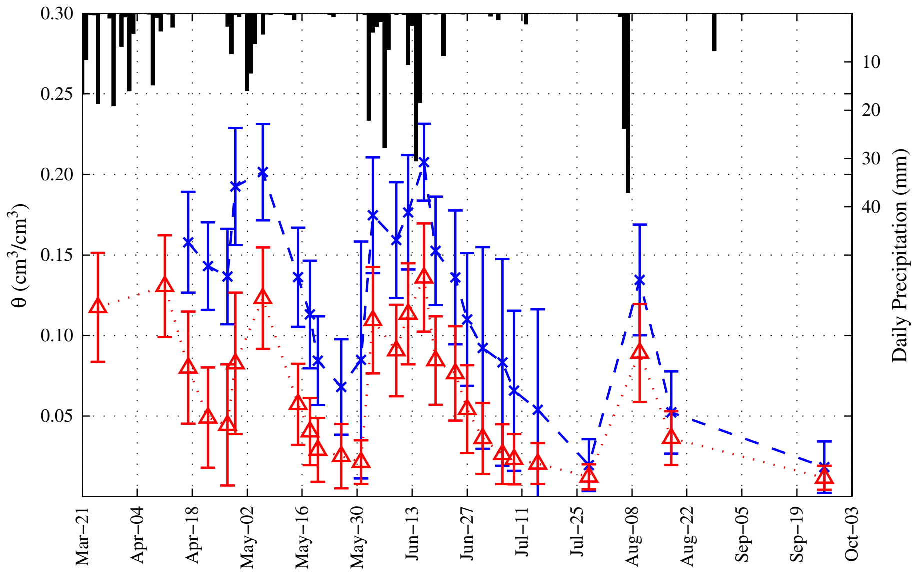

Figure 4. A plot of the average soil moisture conditions on the north (blue) and south (red) aspect slopes is plotted on the left axis; error bars are +/− one standard deviation. Daily precipitation values are plotted on the right axis

aspect slopes are also markedly steeper, a characteristic evident across the Dry Creek watershed. The profound differences observed with aspect have been observed elsewhere (Yetemen *et al.*, 2010) and theoretically predicted (Rodriguez-Iturbe, 2000; Rodriguez-Iturbe *et al.*, 2001), but the complex ecohydrological and geological interactions that lead to those differences remain an area of active investigation. For example, lower insolation on north-facing slopes may result in higher moisture content, promoting vegetation growth. In turn, the presence of the vegetation can stabilize soils or more effectively trap loess material leading to a deeper, more fine-grained soils, The addition of this fine-grained material will promote increased water holding capacity, (e.g., Figure 3) potentially establishing a feedback loop to more vegetation growth. Elucidating such feedbacks will provide deeper understanding of the controls on catchment water storage and long-term relationships between hydrologic processes and landscape evolution.

CONCLUSION

Improved knowledge of catchment water dynamics is predicated on understanding the distribution of landscape properties that promote storage of water. In this study site, north aspect slopes have the capacity to store more water than south aspect slopes due to the presence of finer grained materials and deeper soils, which in turn produce markedly different soil water retention capacity. These differences are presumably driven by differences in insolation; the south aspect soils receive considerably more insolation than the north aspect soils. However, the impact of insolation is complex. While increased insolation has the immediate effect of enhanced drying on south aspect slopes, we suggest that the more salient impact of insolation is on the long-term development of soil properties that promote enhanced storage capacity on north aspect slopes. Future investigations should evaluate the co-evolution of geologic, hydrologic and biologic systems that promote storage capacity.

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